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Structure and Dynamics of Sunspots

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Abstract.

The physics of Sunspots is a fascinating and demanding field of research in solar astronomy. Interaction of magnetic fields and plasma flows takes place in a tangled magnetic geometry and occurs on spatial scales that pose a continuous challenge for existing instrumentation and for the unambiguous interpretation of spectropolarimetric observations. Thus, the main properties of sunspots are well established but its fine structure is not yet fully understood.

In this contribution we summarize the current knowledge of the magnetic and dynamic properties of sunspots at the photospheric level based on selected observations featuring the highest possible spatial and spectral resolution. We concentrate on light bridges, umbral dots, penumbral filaments and the notorious dark cores in penumbral filaments. We report on the morphology of the fine structure elements but mostly focus on observations of their line-of-sight velocities and magnetic field parameters. We briefly comment on results from recent radiative MHD simulations and more schematic model ideas that attempt to rationalize observations of the penumbra.

1. Introduction

The main properties of a sunspot in terms of flows and magnetic field have been very well characterized in the last decades. Sunspots harbour magnetic fields which we now know inhibit at least partially convective energy transport leading to the darker appearance of the umbra which radiates only at 20 % of the flux of the quiet sun and the brighter penumbra which radiates at about 80 % of the flux of the quiet sun.

Flows in the umbra are mostly negligible except in very young sunspots (Sigwarth et al. 1998). The most vigorous flows are observed in the penumbra dominated by the Evershed flow which is interpreted as a horizontal outflow pattern with velocities roughly in the range of 2-6 km/s.

The magnetic field is almost vertical in the umbra with field strengths of about 2-3.5 kG measured by the Zeeman effect and becomes more horizontal in the penumbra where the field strength drops to 700-1000 G at the outer penumbral boundary. Forced by the exponential decrease of density and flux conservation the field lines spread out with height giving rise to a magnetic canopy. Furthermore we know that the penumbra carries a significant fraction of the total magnetic flux which makes it a deep structure as opposed to a shallow structure (Solanki & Schmidt 1993).

Besides its large-scale structure that is stable on the time scale of days to weeks, the penumbra and umbra of sunspots appears to be organized on very

small but dynamic spatial scales (~ 0.1 arcsec). We can assume that the magnetic field and its interaction with plasma flows is the main actor in producing and organizing this fine structure. So a characterization of this interaction that is as accurate as possible is important for inferring and finally understanding the underlying physics.

2. Umbral Fine Structure

Umbral Dots The sunspot umbra is filled with tiny brightenings called umbral dots (UDs). Depending on their location and brightness inside the umbra UD have been either named peripheral UD (PUDs) or central UD (CUDs) (Grossmann-Doerth et al. 1986). Recent results though suggest a different origin of both species (Riethmüller et al. 2008b; Sobotka & Jurcak 2008). On average UD are about 1000 K hotter than the coolest parts of the umbra and only some individual UD reach or exceed the average photospheric brightness and temperature. Observed diameters peak at about 0.23 arcsec corresponding to about 170 km (Sobotka & Hanslmeier 2005). Most UD are known to move towards the more central parts of the umbra or along faint light bridges with proper motions in the range of several 100 m/s (Sobotka et al. 2008; Rimmele 2008). Sometimes UD are found to merge or split (Kitai et al. 2007; Sobotka et al. 2008). There is also ample evidence that UD have a substructure in form of a dark central lane (Rimmele 2008).

Observed Dopplershifts in UD vary over a wide range from unspectacular (Schmidt & Balthasar 1994) to up 1 km/s (Rimmele 2004). Direct measurements of a reduction of magnetic field strength in UD from the splitting of spectral lines show typically values of 5-10 % (Schmidt & Balthasar 1994) sometimes 20 % at the most (Wiehr & Degenhardt 1993). Both parameters, Dopplershifts and measured magnetic field strength reduction, depend on the range of formation heights of the spectral line under consideration.

Inversion techniques that allow us to infer information about the height dependence of the physical parameters show evidence for considerably higher upflow velocities (PUDs) and magnetic field strength reduction (PUDs, CUDs) in the deep layers (close to the formation of the continuum) accompanied also by more inclined magnetic fields that form a (mini-)canopy at least above PUDs (Socas-Navarro et al. 2004; Riethmüller et al. 2008a). The absence of either enhanced flows and inclined fields in CUDs is ascribed to a screening effect caused by their deeper origin.

Lightbridges Another phenomenon encountered in the umbra are light bridges (LBs): bright structures that separate umbral cores or penetrate deeply. Their widths can vary from <1 arcsec to several arcsecs across. Their formation is often observed during either the decay or formation process of a sunspot. LBs appear in very different shapes which might also reflect their evolutionary stage. They can adopt the form of a narrow bright band or of an arrangement of granule-like structures giving a segmented and elevated impression, which is most obvious when observed out of disk center (Lites et al. 2004). At the highest spatial resolution, however, all LBs have in common that they are nerved by a dark central lane associated with a weak upflow (Giordano et al. 2008). Magnetic

fields in LBs are generally weaker (e.g., Katsukawa et al. 2007) and more inclined with respect to the local vertical (e.g., Leka 1997). The gathered information raised the suspicion that LBs constitute a manifestation of magnetoconvection in the umbra (e.g., Rimmele 2004; Berger & Berdyugina 2003; Spruit & Scharmer 2006). This is corroborated by the more recent findings from inversion of high-spatial resolution spectropolarimetric observations (Jurčák et al. 2006). These indicate that LBs are a deep phenomenon formed by field-free (or weak-field) plasma intruding from below forcing the magnetic field in the umbra to form a canopy above most parts of the lightbridge.

Magnetoconvection in the umbra A major breakthrough in understanding the umbra and its fine structure has been achieved by the three-dimensional radiative MHD simulations by Schüssler & Vögler (2006). The simulations show the development of nonstationary narrow plumes of rising hot plasma as a natural result of convection taking place in a strong, initially monolithic magnetic field (about 2500 G). The plumes have a significantly reduced magnetic field strength in their upper layers (down to a few hundred Gauss) and show up in continuum intensity in form of horizontally elongated structures featuring a central dark lane. The central lanes are associated with an upflow while the outer end point of the lanes show adjacent downflows. The dark central lane and its flow signature is interpreted as the direct consequence of radiative cooling effects which lead to a pile-up of plasma and the formation a cusp. The flow turns horizontal below the cusp and the locally increased density and pressure elevates the $\tau = 1$ level to layers with a lower temperature causing the appearance of the dark lane. The elevation of the $\tau = 1$ level can effectively screen the actual properties of the plume because the formation of spectral lines takes part in the layers above the cusp. It should be noted here that the dark lanes observed in LBs likely have a very similar explanation as the one for UD's (Nordlund 2006).

3. Penumbral fine structure

Penumbral Filaments, Penumbral Grains, Dark-Cored Filaments The appearance of the penumbra in intensity is engraved by radially aligned alternating bright and dark structures, the penumbral filaments or fibrils. With good spatial resolution the bright filaments appear as a continuous body with a brighter head of elongated shape, the penumbral grain (PG). In the inner penumbra PGs and the attached filaments show an inward migration towards the umbra (0.5 - 1.5 km/s), while in the outer penumbra an outward migration is observed, defining a very distinct dividing line in the middle penumbra (e.g., Bovelet & Wiehr 2003; Deng et al. 2007).

With the highest spatial resolution the (bright) filament body as well as some PGs reveal a conspicuous and striking internal structure. PGs appear to be split or crossed (Rouppe van der Voort et al. 2004) and the filament body is veined by a dark lane (Scharmer et al. 2002), respectively. The spatial scale of these structures is about 0.12 arcsec. Sütterlin et al. (2004) are the first to report that dark-cored penumbral filaments are mostly observed in the inner center-side penumbra. Langhans et al. (2007) find that the visibility of the dark-cored filaments depends on the heliocentric distance in such a way that it degrades

with increasing distance from sun center. On the centre-side penumbra, however, the dark cores of penumbral filaments are visible for all heliocentric distances. Dark-cored penumbral filaments frequently split in the umbra and form a Y-shape which disappears after a while leaving a shortened filamentary structure and a bright dot in the umbra.

The dark cores in penumbral filaments are usually best identified in integrated (1 nm) G-Band observations at 430.5 nm taking advantage of the higher spatial resolution achieved in the blue wavelength range. However, it appears that they are also more pronounced in narrowband images taken in the line core of spectral lines when compared to the local continuum, which has been taken as evidence for that these structures are elevated above the continuum formation height (Spruit & Scharmer 2006; Rimmele 2008).

Another peculiarity inherent to bright filaments is their twisted appearance caused by intensity fluctuations across the filaments. The twisting motions are observed only perpendicular to the symmetry line, which connects spot center with sun center. The twist direction is oriented from limb- to disk-center side. For more details see Ichimoto et al. (2007a).

4. Flows in the Penumbra

Photospheric Evershed Flow The most conspicuous and vigorous flow in sunspots is the Evershed flow (Evershed 1909). Inside the penumbra spectral lines appear blueshifted on the center-side penumbra and redshifted on the limb-side penumbra. Thus, the Evershed flow is interpreted as a horizontal and radially directed outflow. The Evershed effect does not only manifest itself in form of systematic Doppler shifts but also in line asymmetries of spectral lines that depend on the range of formation heights of the line: weaker (stronger) lines show larger (smaller) line-core Dopplershifts but less (more) asymmetry. For a stronger line the largest line asymmetries and thus velocities are found in the line wing and close to the continuum indicating that the Evershed effect is a deep phenomenon (e.g., Schlichenmaier et al. 2004). The magnitude of the LOS velocity decreases with height (Boerner & Kneer 1992; Rouppe van der Voort 2002) and increases at any given height towards the outer penumbral border where it ceases rather abruptly (e.g., Hirzberger & Kneer 2001). Furthermore, the location of the maximum shifts to larger radial distances when higher photospheric layers (e.g., line core) are probed. To visualize the spatial pattern of the flow field within the penumbra Figure 1 (left) displays a Dopplergram using the line-wing (deeper layers) information of the 630.15 nm line as observed with the Solar Optical Telescope (SOT, Ichimoto et al. 2004) aboard the Japanese satellite HINODE (Kosugi et al. 2007). Noticeable is also the strong filamentation of the flow field into flow channels, which are usually better visible and more pronounced in the center-side penumbra.

Geometry of the flow field A full characterization of the flow field, however, is only possible if the inclination and thus the three dimensional geometry of the flow field can be reconstructed from the observed spectral information. The geometry question is of crucial importance to the more general question that is raised when the Evershed effect is interpreted as a horizontal mass outflow:

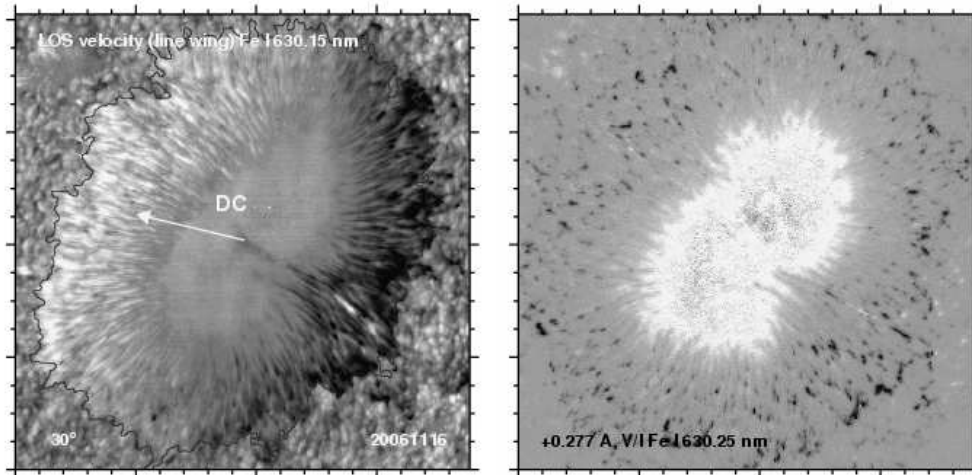


Figure 1. LOS velocity (left) and magnetogram (right) of active region NOAA 10923 observed with the spectropolarimeter aboard the Japanese satellite HINODE on 16 November (out of disk center) and 14 November (disk center), 2006, respectively. The arrow points towards disk center. The LOS velocity is determined from the line-wing information of the 630.15 nm line. Bright indicates blueshifts (towards the observer) dark indicates redshifts (away from the observer). Dopplergram is scaled to a velocity range from -2 to 2 km/s. The magnetogram is taken from the red lobe of the Stokes V signal of the 630.25 nm line. Major tick marks correspond to 20".

where are the sources and the sinks of the flow? The apparent asymmetry between the spatial location of largest blueshifts on the center-side and redshifts on the limb-side penumbra already is an indication that the flow must be inclined. From methods that determine the average flow geometry it has been inferred that in deep layers the average inclination of the flow vector changes with radial distance: it is slightly inclined upwards in the inner penumbra, than becomes horizontal and further outwards returns back to the solar surface (e.g. Tritschler et al. 2004). These results are in agreement with findings that employ a more sophisticated approach like an inversion (Bellot Rubio et al. 2003). In higher layers some part of the flow ($\sim 10\text{-}20\%$) continues upwards to the magnetic canopy (Solanki et al. 1994; Rezaei et al. 2006).

The upflow and downflow component of the flow field, as suggested by the average geometry, are also observed (e.g., Rimmele 1995; Westendorp Plaza et al. 1997; Schlichenmaier & Schmidt 1999). Although this vertical component of the Evershed flow is best and unambiguously identified only in observations at or very close to disk center, evidence also comes from observations of the limb-side penumbra at larger viewing angles. The latter clearly show that the body of the filament flow channels on the limb-side penumbra is mostly associated with a redshift (the Evershed outflow) but the head of the filament (the penumbral grain) shows a very distinct and spatially confined blueshift interpreted as an upflow (Rimmele & Marino 2006). The turnover between upflow and outflow takes place on spatial scales much less than 1 arcsec.

The existence of up and downflows is not limited to the inner and outer penumbra as is demonstrated by magnetograms taken in the extreme red (see Figure 1, right) and blue line wing of the Stokes-V signal: tiny elongated structures associated with a small upflow are observed throughout the penumbra and extended downflow patches are preferably found at the outer boundary but not exclusively (Ichimoto et al. 2007a). Many or most of the downflow patches have opposite polarity from the sunspot. The magnetogram signal is co-spatial with LOS Dopplergram signal which reassures that real velocity signals are detected but more importantly illustrates clearly that the flows occur in a magnetized medium. However, it is difficult to identify pairs of upflows and downflows which leaves the question of mass balance still an open issue.

Velocity-intensity correlation The obvious filamentation of the flow immediately raises the suspicion that the Evershed flow channels must be coupled to the penumbral fine structure as it is observed also in intensity. A positive correlation between intensity and flows (like it is the case for granulation) has been used as an argument for a convective origin of the filamentation altered only by the presence of magnetic fields. In principle it seems plausible that any outcome of such a correlation analysis depends critically on the spatial resolution (besides other factors like e.g. spectral resolution, orientation, radial distance from umbra) achieved in the spectroscopic or spectropolarimetric observations and whether the contribution of the dark cores of penumbral filaments is clearly resolved or not.

In hindsight, the lack of spatial resolution can explain most of the variety of findings of the many observations that attempted to address this question. Observations hint towards either a correlation of flows with dark intensity features (Westendorp Plaza et al. 2001; Rouppe van der Voort 2002), no significant correlation at all (e.g. Hirzberger & Kneer 2001) or a correlation of stronger flows with bright (dark) structures in the inner (middle and outer) penumbra (Jurčák et al. 2007; Jurčák & Bellot Rubio 2008; Ichimoto et al. 2007a). In some cases flow channels connect bright and dark features (Schlichenmaier et al. 2005).

The best available data shows that the Evershed effect seems to be concentrated in the dark cores of penumbral filaments (Bellot Rubio et al. 2005; Rimmele & Marino 2006; Langhans et al. 2007; Bellot Rubio et al. 2007). Bellot Rubio et al. (2005) demonstrate spectroscopically via bisector shapes that dark cores (center side) are associated with strong line-wing blueshifts while the corresponding lateral brightenings show much less LOS velocity signal. It is fair to note that sometimes dark cores exhibit just the same LOS velocity as their flanking brightenings. In a so far unique observation by Rimmele (2008), the LOS Dopplergram of a dark-cored filament channel reveals blueshifts (upflows) associated with the dark core and redshifts (downflows) in the brightenings when deeper layers (line wing) are probed. In higher layers (line core) the same filament shows a blueshift confined to the bright head of the filament and a redshift along the whole filament body without any signature of the presence of the dark core. Whether this observation represents just a one-time peculiarity or describes a common behaviour still needs to be verified.

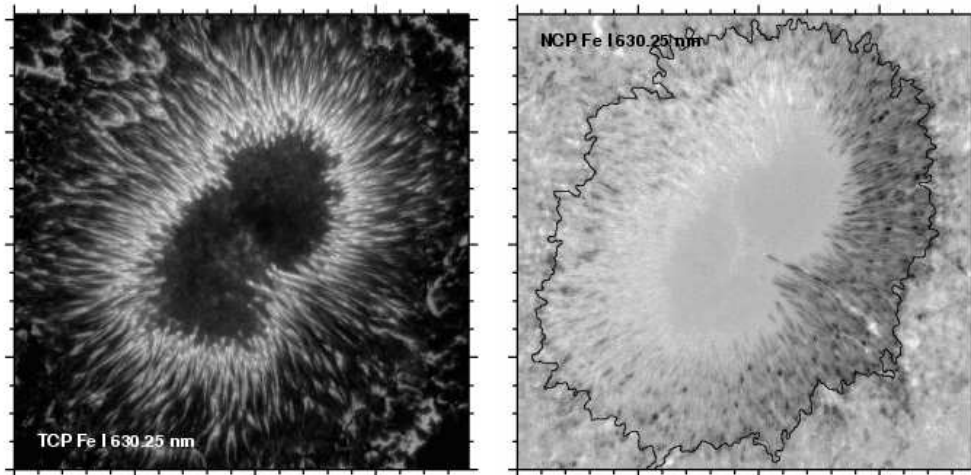


Figure 2. Total circular polarization (left) and NCP (right) of active region NOAA 10923 observed in the Fe I 630.25 nm line with the spectropolarimeter onboard the Japanese satellite HINODE on November 14 (disk center) and November 16 (out of disk center), 2006, respectively. Major tick marks correspond to $20''$.

5. Magnetic Fields in the Penumbra

Fluted Penumbra Sunspots do not only show a filamentary structure in intensity and the flow field but also in polarized light as visualized in Figure 2(left). The azimuthal inhomogeneity of the penumbral magnetic field on small scales is well established going back to the early findings of Beckers & Schröter (1969). The penumbra appears to be “fluted” on small spatial scales (Title et al. 1993; Langhans et al. 2005). A different signal in circular polarization can either indicate different magnetic field strength or a different inclination and it needs either an inversion of spectropolarimetric data or some other technique to disentangle these two effects. It turns out that two components can be separated: one which harbours more vertical and stronger fields, and one showing weaker and more inclined fields, which have been named spines and intra-spines, respectively (Lites et al. 1993; Borrero & Solanki 2008; Borrero et al. 2008). For a very thorough characterization of these two magnetic components see also Bellot Rubio et al. (2004). In general, the conclusion is that the azimuthal fluctuation of polarization is caused by a combined effect of varying field inclination and field strength. Furthermore, the dark cores in penumbral filaments tend to have more inclined and weaker fields and also are the location where the Evershed flow is concentrated (Langhans et al. 2007; Bellot Rubio et al. 2007).

Stokes Asymmetries, NCP An alternative and more direct way to extract information about how the magnetic field is related to flows, is to examine the asymmetry of the Stokes parameters with wavelength (e.g., Sánchez Almeida & Lites 1992). In particular the wavelength integrated Stokes V profile, the net-circular polarization (NCP), provides a simple and instructive way of characterization. The NCP, although a condensed quantity, is of diagnostic importance because

apart from the Evershed effect it is a very critical observation that any model of the penumbra must reproduce. The spatial behaviour of the NCP is symmetric in the inner and middle penumbra w.r.t. the line that connects the disk center with the spot center (see Figure 2, right). The same property applies to the LOS velocity which already indicates an intricate coupling between penumbral flows and the sign of the NCP. This is corroborated by the fine structure of the NCP, which reveals filamentary organized inhomogeneities throughout the penumbra with very localized enhancements of elongated shape on very small spatial scales. Furthermore, there appears to be a difference in the symmetry properties of the NCP observed between the limb- and center-side penumbra, namely a sign reversal of the NCP in the outer center-side penumbra (Tritschler et al. 2007). In anticipation of a coupling between flows and the NCP ground-based observations have had difficulties to establish suchlike conclusively. However, seeing-free spectropolarimetry suggests a correlation between the two quantities. The positive NCP is co-spatial with flow channels on the center- and limb-side penumbra, while a negative NCP is co-spatial with locations in between the flow channels (Ichimoto et al. 2008).

6. Schematic Models of the Penumbra

Uncombed Structure In an attempt to master some of the observations, particularly the asymmetries of the Stokes parameters and the azimuthal variation of the polarization signal, Solanki & Montavon (1993) proposed the concept of the uncombed penumbra. It is the simplified idea of more or less horizontal flux tubes that carry the Evershed flow and which are embedded in a more vertical background magnetic field. There exist different realizations of the uncombed penumbra but in all these models sharp gradients in velocity and magnetic field parameters are encountered at the interface between the flux tube and the background that can contribute to the generation of the observed NCP. Velocity gradients are a necessary condition though to produce a NCP. The early two-dimensional models (Solanki & Montavon 1993; Martínez Pillet 2000) do reproduce observed properties of the NCP but are limited to a few geometric cases. More importantly, they cannot provide any information about the spatial distribution of the NCP within the penumbra. In a more sophisticated approach this downside was overcome by a three-dimensional model incorporating a snapshot of the moving tube model embedded in a static background atmosphere (Müller et al. 2002, 2006). In particular, this approach allowed to identify the discontinuity in the apparent azimuth of the magnetic field (between flux tube and background as measured in the observers coordinate system) and anomalous dispersion as the main cause of the characteristic spatial pattern of the NCP when observed in the infrared at 1564.8 nm.

Field-Free Gaps in the Penumbra In order to explain the observed brightness of the penumbra and inspired by the striking morphological similarities between UD, LBs and penumbral filaments (dark central lanes), Spruit & Scharmer (2006) and Scharmer & Spruit (2006) proposed and investigated radially aligned field-free plumes where convection can take place thus promoting an all-embracing picture of the fine structure in sunspots. The gappy penumbra has since then

challenged the concept of penumbral flux tubes. The magnetohydrostatic model predicts a field topology above the field-free gaps that changes from cusp-shaped in the inner to canopy-shaped in the outer penumbra. Hence, the field geometry above the gaps together with the convective flows inside the field-free gaps provides gradients and discontinuities that in principle could lead to a NCP, but unfortunately this has not been demonstrated yet. The Evershed flow is interpreted as the horizontal flow component of convective motions in the field-free gaps. For the most recent discussion of this approach see Scharmer (2008).

Obviously, a crucial question that must be answered by any model of the penumbra is how the observed penumbral heat flux ($\sim 75\%$ of the quiet sun) can be accounted for. Convective motions in field-free gaps solve this problem in a natural way while on the other hand, the hypothetical interchange convection (e.g., Jahn & Schmidt 1994) alone cannot account for the brightness of the penumbra (Schlichenmaier & Solanki 2003). However, in an extension of the work performed by Schlichenmaier et al. (1999), Ruiz Cobo & Bellot Rubio (2008) demonstrate that thick flux tubes carrying a (hot) Evershed flow can explain the surplus brightness of the penumbra (see also Schlichenmaier & Solanki 2003).

Observational evidence In either model, the uncombed or gappy penumbra, the magnetic field has to close or wrap around either the embedded flux tube or the field-free gap which would show up in the form of an opposite sign of the azimuth angle on both sides above the penumbral filaments. Such field wrapping has been recently inferred from inversions of seeing-free spectropolarimetry further corroborating the strong spinal (stronger fields) and intra-spinal (weaker fields) structure of the magnetic field (Borrero et al. 2008).

A type of roll-over convection in penumbral filaments is mediated by the aforementioned apparent twist that is seen in continuum intensity space-time plots taken across the filaments (Ichimoto et al. 2007b). The character of that twist strongly suggests that it is the result of a viewing angle effect instead of being caused by an actual helical motion of the filaments (see also Zakharov et al. 2008). For a different interpretation see Ryutova et al. (2008).

In deeper layers Rimmele (2008) directly observed redshifts associated with the bright flanks of a dark penumbral core showing blueshifts. In higher layers the same filament shows blueshifts in the PG and redshifts along the filament body. Notwithstanding the so far unique but also ambiguous nature of this observation, it must be viewed as evidence for convection in penumbral filaments.

7. Simulations of Penumbral Fine Structure

Sunspots pose a very challenging regime for modelers studying magneto-convection. The situation for the penumbral fine structure is particularly complicated by the presence of oblique fields and the larger spatial scales (horizontal and vertical) that must be taken into account. All the more impressive appear the most recent attempts of Heinemann et al. (2007) and Rempel et al. (2009) that try to tackle the difficult regime encountered in the penumbra. Both numerical simulations encompass three-dimensional MHD including grey radiative transfer.

Apart from morphological differences both simulations in principle show similar results like the development of more or less evolved filamentary structures established by gaps with reduced field strength. The horizontal component of overturning or roll-type convection in these gaps provides an explanation for the Evershed flow. The flow speeds, however, are much smaller than the actual observed ones. The dark-cored structures that are associated with weaker and more horizontal fields harbour an outflow and migrate inwards. At the outer boundary of this rudimentary penumbra fragments of flux are carried away by a large scale moat flow that develops as well during the simulation. It is yet very striking, that although individual filaments do develop, there is no evolved penumbra, meaning the penumbra is not filled with filaments. This is currently not understood.

8. Concluding Remarks

We finally see exciting simulations of radiative MHD coming to a realistic state including also the penumbra. A very important step will be to demonstrate that these simulations can reproduce the observations not only from a morphological standpoint but also from a spectroscopic perspective. There is a wealth of spectropolarimetric information that needs to be explained. Therefore, it is the next logical step to perform spectral synthesis based on these simulations to allow for a direct comparison with the observations in the important wavelength bands of the visible and the infrared.

In the mean-time we have to rely further on high-resolution observations (spectrally, spatially and temporally) provided by improved instrumentation, image reconstruction techniques and interpretational tools like inversion codes which are necessary to derive the magnetic field geometry while nevertheless keeping in mind the limitations of their diagnostic capabilities.

In a future attempt the photospheric structure must be tied to the chromospheric structure of sunspots and important questions like (a) what is the cause of the inverse Evershed effect, (b) what is the magnetic field structure in the chromosphere and (c) how does it relate to the uncombed fields observed in the photosphere? must be addressed.

With the launch of HINODE a stable window to the Sun opened, providing a spatial resolution close to the diffraction limit of its telescope. Hence, the joint effort of ground-based and space-borne observations should lead to substantial progress in characterization of the various small-scale inhomogeneities observed in sunspots.

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